Mechanical Tests of Material from the Hagia Sophia Dome

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Bond and tensile strength testing of part of an unusually large brick-mortar sample obtained by Robert Van Nice in 1949, during a repair to a rib of the main dome of Hagia Sophia, was performed last summer. The sample, comprising a mortar "sandwich" between two bricks (Fig. 1), was logged in as Dumbarton Oaks "mortar sample M-26 from the base of rib 7 at the west face of the main dome" and dated by Van Nice to A.D. 558–563. Many other specimens of building material from Hagia Sophia were also collected, but none of these is large enough to permit the types of tests reported on here.

The brick-mortar sample was first sawn in half in the geology laboratory at Princeton, allowing the return of a substantial, undamaged segment of the sample to Dumbarton Oaks for future display. Also, since only the upper brick in Figure 1 was actually joined to the mortar, the loose, lower brick was not removed for testing.

The adhesion test specimen, having a brick-mortar interface surface 9.50 cm long × 2.35 cm in width, was then formed from the remaining portion of the sample (Fig. 2). The standard adhesion test is actually a measure of shear strength through the determination of the force necessary to cause the mortar to *slide* along the brick. It is generally performed in a precision test machine, one of the elements being rigidly held while a calibrated shearing force is applied to the other. In our test, the loading was offset 2° from the interface axis in order to reduce local shear stress concentration at the interface boundaries.[1] Even so, the brick separated at a load of 27.3 kg (60 lbs), giving an *average* shear stress across the interface of 1.22 kg/cm² (17.5 psi). Observation of the fractured surface indicated remaining regions of adhesion between the brick and mortar over about 30% of the interface (Fig. 3). Comparable test data for ancient materials is not generally available in the literature.

The separated portions of brick and mortar resulting from the adhesion test were then trimmed to form three prismatic specimens for modulus of rupture testing (tensile strength determinations from beam bending tests). The brick test specimen, having a cross-section 1.55 cm deep × 1.63 cm wide and spanning 8.25 cm, failed under a central loading of 9.53 kg. Mortar specimen No. 1, with cross-section dimensions 2.34 cm deep × 2.29 cm wide, failed under a loading of 4.72 kg applied at the center of a 7.62 cm span; mortar specimen No. 2, with cross-section dimensions 2.29 cm deep × 2.29 cm wide, failed similarly under 5.71 kg. Failures of both mortar specimens seemed to initiate at inclusions. Calculated tensile stresses at failure (i.e., tensile strength) from the three tests are: 30.1 kg/cm² (427 psi) for the brick; 4.30 kg/cm² (62 psi) for mortar specimen No. 1; and 5.44 kg/cm² (78 psi) for mortar specimen No. 2. Although these tests do not provide meaningful statistical data, probably the most interesting result is the fact that the tensile strength of the Byzantine mortar is indicated to be two to three times the reported strength of specimens of medieval lime mortar.[2]

Densities were also determined from making precise dimensional measurements of the

[1] R. Mark, "Mortar Shear-strength Test Fixture Design," unpublished report to the Tile Council of America, Princeton, N.J., 29 January 1979.

[2] H. Masson, "Le Rationalisme dans l'Architecture du Moyen Age," *BullMon* 94 (1935), 29–50.

specimens and weighing them with an electronic scale. The density of the brick was found to be 1540 kg/m^3 (96 psf) and 1430 kg/m^3 (89 psf) for the density of the mortar, indicating that the dome rib was composed of relatively lightweight masonry. Chemical testing to determine the composition of the brick and mortar fragments from the mechanical tests are now being performed at three laboratories: the Princeton Materials Institute at Princeton University, the Materials Science Laboratory of the National Technical University of Athens, and the Materials Laboratory of the Politecnico di Milano.

All of these data are most important for the modeling and in situ experimental study of the Hagia Sophia structure being carried out in Princeton and in Istanbul (under joint sponsorship of the National Endowment for the Humanities, the National Science Foundation, the A. W. Mellon Foundation, and the Ministry of Culture of Turkey) aimed at better interpreting design and construction, and securing the monument against future earthquakes.[3]

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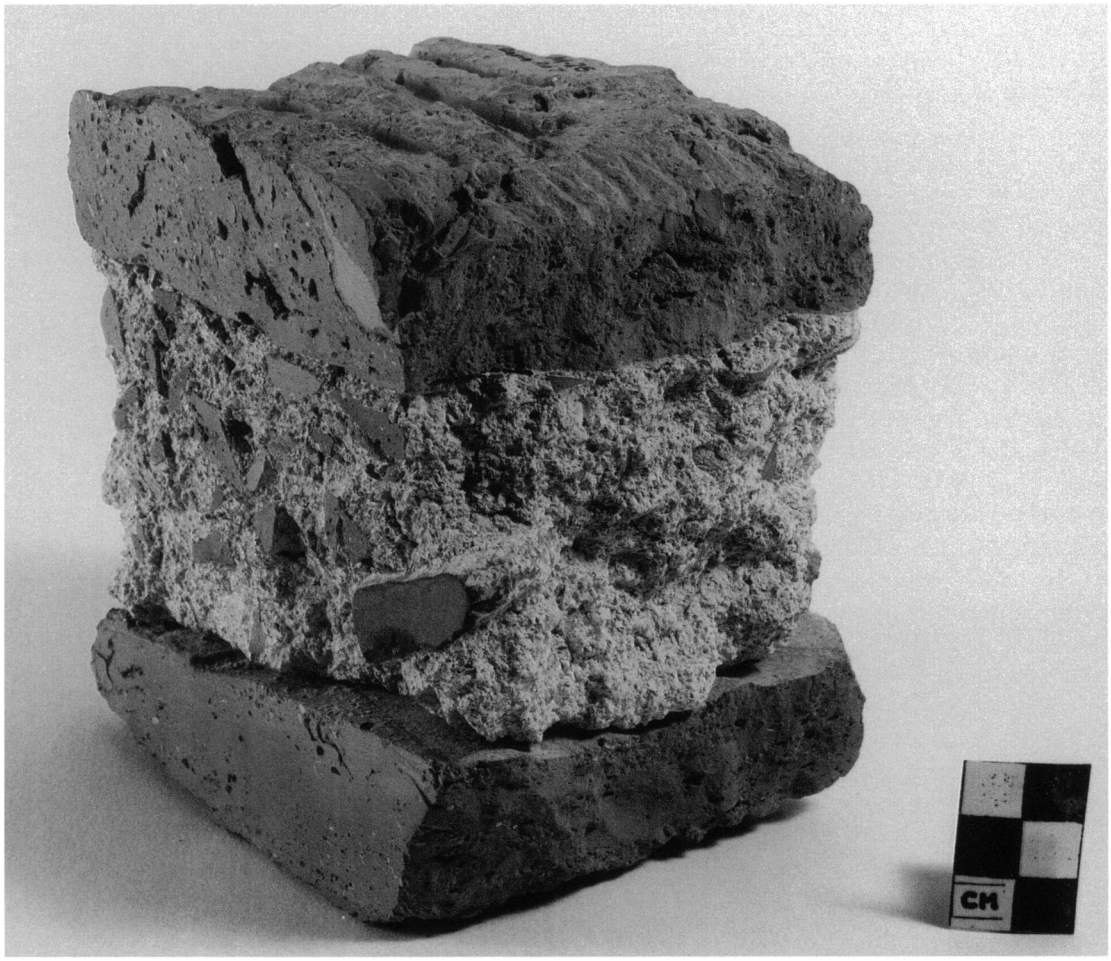
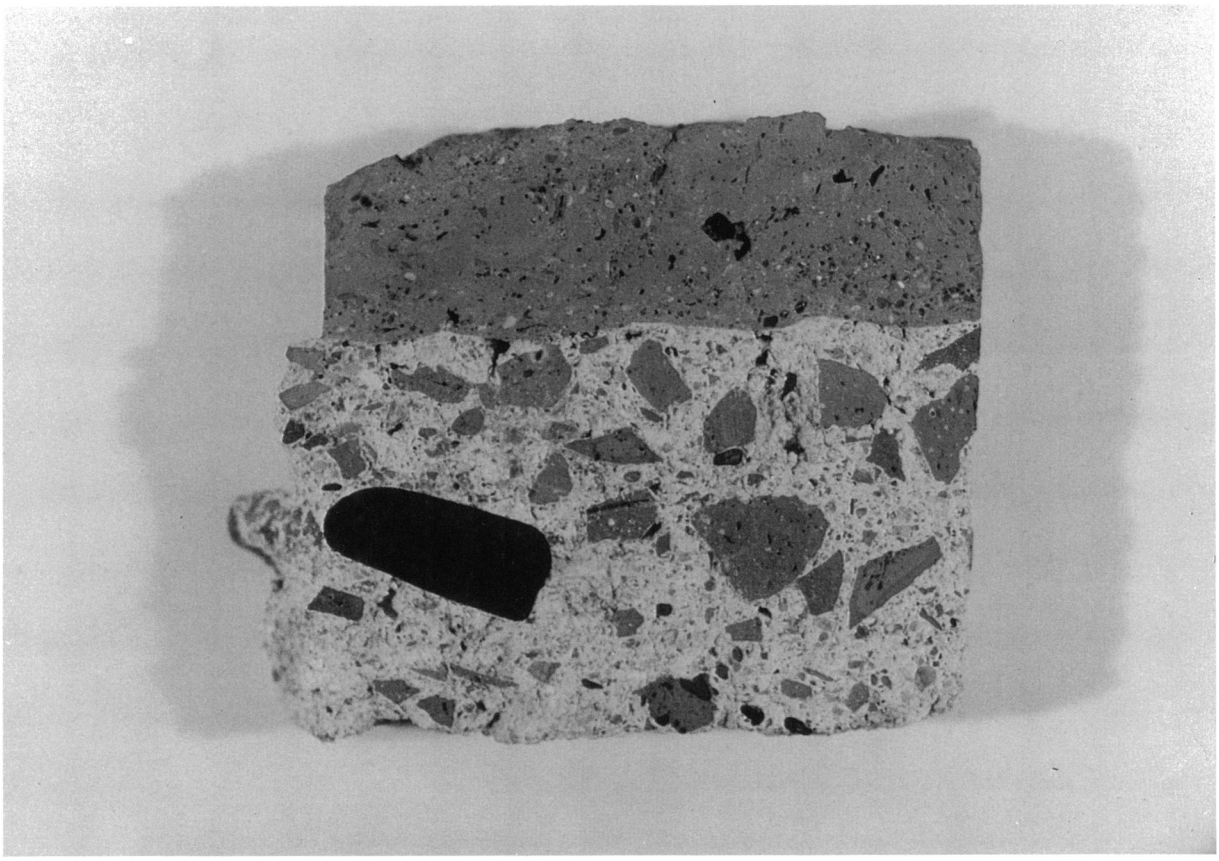
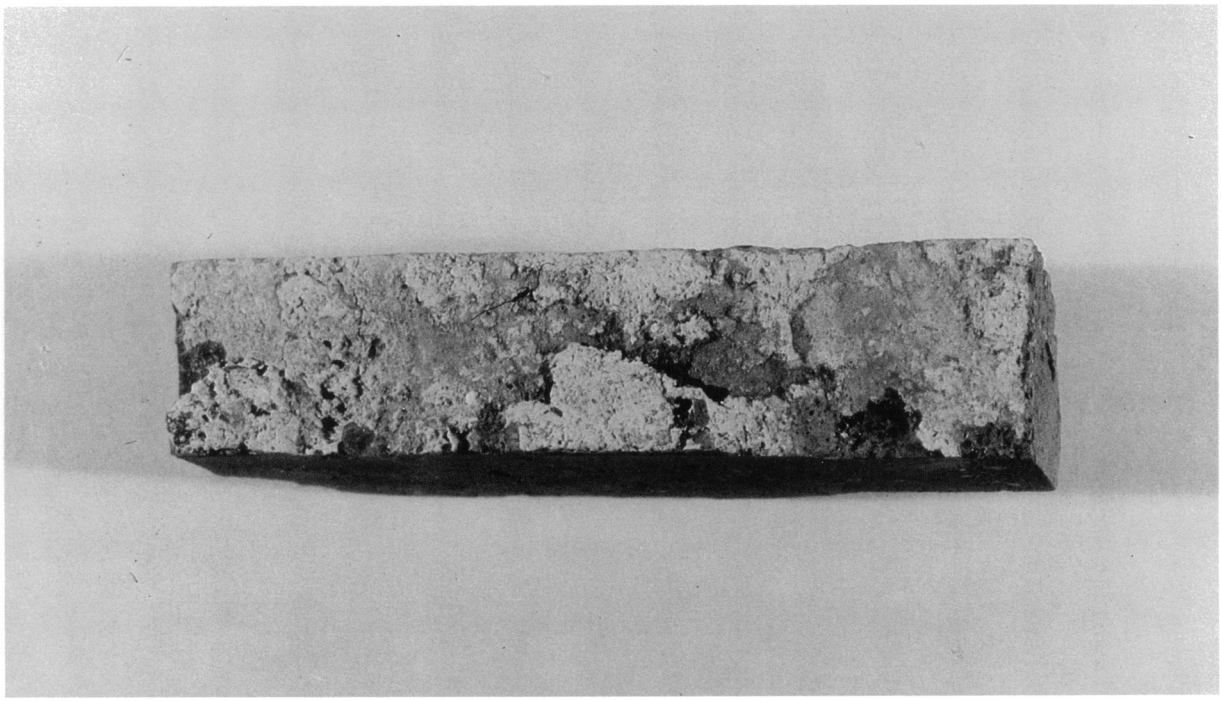
[3] R. Mark and A. S. Cakmak, *Hagia Sophia from the Age of Justinian to the Present* (Cambridge, 1992).



1 Hagia Sophia mortar sample M-26 (photo: Dumbarton Oaks)



2 Adhesion test specimen (note the relatively large fragments of brick and stone included within the mortar)



3 Surface of the brick interface after adhesion testing.